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RESEARCH MEMORANDUM

CONTROL DURING STARTING OF GAS-TURBINE ENGINES

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

An investigation of the variables pertinent to the control of gas temperatures of gas-turbine engines during starting was conducted by obtaining time records of the variables involved during actual starting conditions. All studies were conducted at static sea-level conditions, using a centrifugal-compressor, through-flow-type turbojet engine.

Poor control of gas temperatures during starting is caused by an accumulation of fuel in the engine before ignition and by excessive fuel-flow rates at the time of ignition. The use of well-atomized fuel sprays improves ignition and thus reduces fuel accumulation. If the fuel is sufficiently atomized, it remains suspended in the air stream flowing through the engine. Substantial reductions in starting energy requirements result from firing the engine at speeds below normal firing speed, as permitted by improved control of gas temperatures.

INTRODUCTION

High temperatures that exist during some starting cycles of gas-turbine engines limit engine operating life. Failures of such engine parts as burner liners, turbine-nozzle blading, turbine blading, exhaust cones, and tail pipes have been attributed to excessive gas temperatures encountered during starting. Army specifications for the engine used in this investigation require that after starting the engine three times with tail-pipe gas temperature exceeding 1832° F, the engine should be dismantled for inspection.

Current American engines are provided with a manual starting control, which depends on the operator's skill for maintenance of gas temperatures during starting within allowable limits. An automatic starting-sequence control has been developed in Great Britain, which is now in use on at least one turbojet engine (reference 1).

An experimental investigation of control during starting of a turbojet engine was conducted at the NACA Cleveland laboratory. The problem of control during starting is believed to be similar for all types of gas-turbine engine. Control is defined herein as the response of gas temperatures to changes in fuel flow. The objects of the investigation were: (a) to determine the causes of poor control that may lead to excessive gas temperatures during starting; (b) to determine means of improving control of temperatures during starting; and (c) to study the effect of variations in the starting cycle on the starting power and energy requirements.

The investigation was made by obtaining time records of the variables involved during actual starting conditions. Data were first obtained during starting of an unmodified centrifugal compressor, through-flow-type turbojet engine. The fuel system was then so modified as to improve ignition and to permit firing of the engine at lower fuel flows than those required with the original fuel system. All studies were conducted at static sea-level conditions.

APPARATUS AND PROCEDURE

Engine. - The engine used for this investigation (fig. 1) consists essentially of a centrifugal compressor, 14 through-flow combustion chambers, a single-stage turbine, and a tail-pipe-nozzle assembly. The maximum rated engine speed is 11,500 rpm and the idling speed is 4000 rpm. A tail pipe, 60 inches long and 21 inches in diameter, and a conical exhaust nozzle having an outlet diameter of 19 inches were used.

A sketch of a combustion chamber (fig. 2) indicates the position of the fuel nozzle, spark plug, inner liner, and cross-ignition tube. Two spark plugs, located in combustion chambers 180° apart, are provided on this engine. Cross-ignition tubes between the combustion chambers provide ignition for the fuel in the other combustion chambers. The seven combustion chambers on the lower half of the engine are fitted with a manifold and a valve assembly, which permit unburned fuel to drain from these combustion chambers. The drain valve is designed to allow fuel to drain when the combustion-chamber pressure is below 2 pounds per square inch gage.

Fuel system. - Three sets of 80° hollow-cone spray fuel nozzles were used during the investigation. Two of the sets were of the fixed-orifice type (fig. 3(a)), rated at 40 and 10$\frac{1}{2}$ gallons per hour with a nozzle-tip pressure differential of 100 pounds per square inch. The 40-gallon-per-hour nozzle will hereinafter be referred to as the "large" nozzle, and the $10\frac{1}{2}$-gallon-per-hour nozzle as the "small" nozzle. The large nozzle is standard equipment on the engine used for this investigation. The small-nozzle assembly had the metering unit removed (fig. 3(a)). The third set of nozzles was of the variable-orifice type (fig. 3(b)). Both sets of fixed-orifice nozzles were used in conjunction with a conventional fuel manifold. The variable-orifice nozzles, designed to open at a pressure differential of 50 pounds per square inch across the nozzle tip, were used in conjunction with a metering control (reference 2) to obtain equal fuel-flow rates to all nozzles. The pressure-flow characteristics of the various nozzles used are given in figure 4.

Auxiliary electrically driven fuel pumps were used in parallel with the main engine driven pump to provide sufficient fuel pressure during engine starting. With the large nozzles and the variable-orifice nozzles, an auxiliary pump, rated at 5 gallons per minute and 150 pounds per square inch, was used. A similar auxiliary pump is used on aircraft installations of the engine used in this investigation. When the small nozzles were used, the main pump was connected in parallel with an auxiliary pump rated at 10 gallons per minute and 480 pounds per square inch. The auxiliary pumps were used only while the starting motor was energized.

The fuel used for all engine operation was kerosene, AN-F-32.

Electrical system. - Two 12,000-volt transformers were used in the ignition system. The starting motor was operated from an external direct-current source. Provision was made for varying the starting-motor output by use of resistance in the electric circuit.

Instrumentation. - Instrumentation used to measure exhaust-cone gas temperature differed slightly from that used on aircraft installations. Four chromel-alumel thermocouples were located at the exit of the exhaust cone (fig. 1, station 1). These thermocouples were connected in parallel to a recording potentiometer having a response rate of 200° F per second. The location of typical aircraft instrumentation, consisting of two thermocouples connected in parallel, is indicated in figure 1, station 2. Engine speed was measured by an electric recording tachometer. Other recording instruments were used to measure the fuel pressure supplied to the spray nozzles and the current and the voltage supplied to the starting motor.

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The air flow to one combustion chamber was determined by an air-survey rake consisting of three total-pressure tubes and two static wall taps fitted to one of the air-adapter spacer plates. The survey rake was calibrated under simulated engine air-flow conditions against a commercial adjustable-area orifice. A schematic drawing of the calibration installation is shown in figure 5. The engine was operated at speeds from 9 to 30 percent of maximum engine speed to obtain air-flow data in the starting range. The engine air-flow calibration thus obtained (fig. 6) was used to determine fuel-air ratio. The accuracy of this calibration is unknown but is unimportant because it was used only to obtain a qualitative comparison of fuel-air ratios during the various starting procedures.

Procedure. - For all starting conditions, the ambient-air temperature was between 40° and 60° F. During periods of controlled combustion, the exhaust-gas temperature was maintained at 1500° F by manipulation of the fuel-throttle valve. The conventional starting procedure, which was used as a basis in this investigation, was carried out in the following manner:

1. The auxiliary fuel pump was energized and the starting motor engaged.

2. At 9 percent of maximum engine speed (1035 rpm), the ignition circuit was closed and the fuel stopcock and the throttle valve were opened. The throttle opening was determined by the fuel flow required to obtain ignition with the set of fuel nozzles being used. Approximate settings were: (a) large nozzles, one-half open; (b) small nozzles, one-fourth open; and (c) variable-orifice nozzles, idle position.

3. At 17 percent of maximum engine speed (1955 rpm), the starter and the auxiliary fuel pump were disengaged.

RESULTS AND DISCUSSION

Causes of Poor Gas-Temperature Control

The unmodified engine was started a number of times according to the conventional procedure in order to study the conditions that exist during starting. Time records of the fuel flow, fuel-air ratio, exhaust-gas temperature, and engine speed during starting were obtained. A typical starting record is shown in figure 7. The time scale was so chosen that zero time was the time at which the fuel-manifold pressure began to rise. In order to maintain the gas temperatures at the values shown, the fuel flow was reduced to that of the idle fuel-flow setting immediately after ignition. It was thus necessary for the operator to anticipate the trend of the gas temperature, inasmuch as it did not follow the trend of the fuel flow. This characteristic was noted in all starting conditions of the engine using the large fuel nozzles. The exhaust-gas temperature, however, did not exceed 1832° F during any starting period in which the engine was brought up to 9 percent of maximum speed before turning on the ignition and the fuel. Exhaust-gas temperatures exceeding 1832° F were obtained when the engine was fired at 5 percent of maximum speed (fig. 8). In this case, poor control led to excessive gas temperatures.

The fuel did not burn at the rate at which it was supplied, as indicated by the data of figures 7 and 8. A lag occurred between the time fuel was supplied and the time ignition occurred, during which fuel wet the interior of the engine, accumulated in the tail pipe, and drained from the combustion chambers. The fuel-flow rate required to obtain ignition in all burners was approximately 60 pounds per hour per nozzle, giving fuel-air ratios of 0.04 or greater. The fuel-air ratio at the time of ignition was more than twice the value obtained during acceleration some 30 seconds later. These factors indicate that poor control of temperatures during starting was caused by an accumulation of fuel in the engine before ignition and by the high fuel-flow rates required for ignition.

Ignition lag. - The fuel-flow rate required for ignition and ignition lag is directly related to the fuel nozzles used. With fixed-orifice fuel nozzles, the pressure and the flow must increase to values at which a sufficiently atomized fuel spray is supplied in the region of the spark plug. The atomization must also be adequate in the combustion chambers not provided with spark plugs to permit complete ignition of the fuel by means of the cross-ignition tubes. The degree of atomization and the position of the spray cone relative to the spark plug that existed at two fuel-flow rates with the large fuel nozzles are shown in figure 9. Absence of fuel near the ignition source at the low rate (fig. 9(a)) explains why a fuel-flow rate as high as 60 pounds per hour from each nozzle was required for ignition.

The ignition process for the combustion chambers not provided with spark plugs is shown by photographs taken during a typical start (fig. 10). These photographs were taken looking toward the turbine wheel with the tail cone, exhaust pipe, and jet nozzle removed from the engine. Combustion chambers having spark plugs were located at the 11 and 5 o'clock positions. The time required for combustion to spread to all of the chambers was approximately 5 seconds.

Fuel accumulation. - In order to separate the effect of high fuel flow at the time of ignition from the effect of accumulated fuel in the engine, the flow rate was reduced by using the small nozzles. With these nozzles, ignition could be obtained at a flow rate that could be maintained during the starting period without causing excessive temperatures. The results of starting with the ignition spark delayed to provide time for fuel to accumulate are shown in figure 11. Excessive temperatures over which the operator had no control were caused by fuel accumulated during ignition delay. If all the fuel supplied the engine before ignition burned in 4 seconds following ignition, the fuel-air ratio during that period would be approximately 0.04, as indicated by the dashed curve in figure 11. Because of instrument limitations, the indicated rate of temperature rise shown in figure 11 is somewhat less than the true rate.

Fuel-flow rate. - Because of poor combustion efficiency when starting with the large nozzles, the gas temperatures during starting were not excessive, as shown by figure 7, even though the fuel-air ratio reached 0.04. With improved combustion efficiency, which was obtained by better atomization, high fuel-flow rates would cause high gas temperatures. This trend is shown in figure 12, which presents data obtained using the small fuel nozzles. Again the temperature-rise rate shown is somewhat less than the true rate.

Improved Control of Temperatures during Starting

The data obtained indicate that poor control of temperatures during starting is caused by an accumulation of fuel before ignition and by high fuel flows at the time of ignition. In order to demonstrate the starting characteristics obtainable with these causes eliminated, the engine was started a number of times using the small fuel nozzles. The data of figure 13 were selected as representative of the improved starting characteristics. Obtaining ignition quickly at a fuel-air ratio of approximately 0.02 and maintaining this value during acceleration gave well-controlled starting without excessive temperatures.

The degree of atomization and the position of the spray cone relative to the spark plug that existed during starting conditions when the small nozzles were used is shown in figure 14. The lapse of time after ignition has occurred in those burners provided with spark plugs is indicated by the photographs of figure 15. A comparison of the starting characteristics with the large and the small fuel nozzles follows:

	Large fuel nozzles (figs. 7 and 10)	Small fuel nozzles (figs. 13 and 15)
Ignition time lag from fuel-manifold pressure rise until initial temperature rise, sec	7	2
Fuel flow per nozzle at time of ignition, lb/hr	60	20
Total fuel supplied before ignition, lb	1.53	0.133
Fuel-air ratio immediately following ignition assuming no accumulated fuel	0.04	0.02
Estimated time from initial ignition until all burners had been ignited, sec	5	2

The use of a fixed-orifice nozzle small enough to give good atomization during starting would require very high fuel pressures to cover the engine operating range. High pressures can be avoided, however, by use of duplex nozzles, which have been used on some engines, or by the use of variable-orifice nozzles. Both types of nozzle offer a means of obtaining ignition at low fuel flows and of covering a wide range of flows at pressures that are not excessive.

At the low fuel flows required for starting, the variable-orifice fuel nozzles investigated gave better atomization than either of the two sets of fixed-orifice nozzles. With these nozzles, a higher pressure was used at low values of fuel flow, as will be noted by comparing the pressure-flow characteristics (fig. 4). The degree of atomization and the position of the spray cone relative to the spark plug that existed during starting when using the variable-orifice nozzle is shown in figure 16. With good atomization, fuel does not accumulate in the engine even though ignition is delayed. The engine was started after the ignition was delayed 34 seconds without obtaining excessive temperatures (fig. 17). The fuel droplets remained suspended in the air stream and were carried through the engine.

Effect of Starting Cycle on Starting Requirements

With good control of gas temperatures during starting, the effect of changes in the starting cycle on power and energy requirements for a constant exhaust-gas temperature (1500° F) was investigated. The power and energy requirements for normal starting, using the large fuel nozzles and firing the engine at 9 percent of maximum speed, are shown in figure 18. The time interval at 9 percent maximum engine speed is caused by ignition lag. After ignition, the engine was accelerated by the starter plus the turbine until 17 percent of maximum speed was reached, at which time the starter was disengaged. The total energy required during normal starting was 110 watt-hours. The starter and turbine power outputs were calculated using the moment of inertia of the rotating mass of the engine, the acceleration rate during starting, the deceleration rate without combustion, and the energy input to the starter. Details of the method used are given in the appendix.

The remainder of the investigation was conducted using the small fuel nozzles. The improved atomization from these nozzles gave a reduction in starting energy when the normal starting cycle was followed (fig. 19). This reduction in starting energy was caused by a reduction in the ignition-lag period and improved combustion efficiency.

In the study of starting cycles, two types of change were made. The power supplied by the starting motor was first reduced in successive steps and the engine fired at the reduced speeds thus obtained. Starting-energy requirements decreased with each reduction in firing speed. The power and energy requirements during starting in which the engine was fired at $4\frac{1}{2}$ percent of maximum speed are shown in figure 20. The power supplied by the starter was approximately one-seventh of that used in normal starting, the peak current was much lower, and the energy was approximately one-half of that required in normal starting; however, the total time was appreciably increased. In the other type of cycle, the engine was fired at reduced speeds during acceleration by the starter, using the full starting power available. The time and energy required for starting were reduced with each reduction in firing speed. The starting characteristics when the engine was fired at 4 percent of maximum speed is shown in figure 21. This speed was the lowest at which the engine could be fired and at the same time maintain adequate control of gas temperatures. Practically a straight-line increase in speed was obtained; the total starting time was approximately one-half normal. The starting energy was less than one-half of the normal requirements.

The data show that a considerable reduction in starting energy may be obtained by firing the engine at lower speeds. The starter power could be reduced somewhat, which would increase the time required for starting. For minimum starting time and energy, it appears desirable to fire the engine before the starter reaches its maximum speed.

CONCLUSIONS

The following conclusions are based upon an investigation of the static sea-level starting characteristics of a centrifugal-compressor, through-flow-type turbojet engine but are believed to be applicable to other types of gas-turbine engine:

1. Poor control of gas temperatures during starting is caused by the accumulation of fuel in the engine before ignition and by excessive fuel-flow rates at the time of ignition.

2. The use of well-atomized fuel sprays improves ignition and thus reduces fuel accumulation. If the fuel is sufficiently atomized, it remains suspended in the air stream flowing through the engine.

3. Substantial reductions in starting-energy requirements result from firing the engine at speeds below normal firing speed, as permitted by improved control of gas temperatures.

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APPENDIX - METHOD OF CALCULATING STARTER AND TURBINE POWER OUTPUT

The total power required to bring the engine up to a given speed is equal to the sum of the steady-speed power, which is defined as the friction and compressor power, and the acceleration power. These two power increments were calculated from speed and time data, which were taken during deceleration without combustion and during acceleration. The starter output below the firing speed was thus obtained. Above the firing speed, the total power required to accelerate the engine is the sum of the starter and turbine outputs. The power output of the starter above the firing speed was obtained from power input data and the efficiency of the starting motor. Starting-motor efficiency was obtained from the power input and output below the firing speed and was extrapolated above this range. The power output of the turbine was obtained by subtracting the starter power output from the total power required to accelerate the engine.

The calculations were made using the following equations:

Torque

$$T = \left(\frac{I}{g}\right)\left(\frac{\Delta N}{sec}\right)\left(\frac{2\pi}{60}\right)$$

Horsepower output

$$HP = \frac{2\pi\ NT}{33,000}$$

Horsepower input

$$HP = \frac{VA}{746}$$

where

T torque, ft-lb

I moment of inertia of rotating mass, 175 lb-ft^2 for engine used

g acceleration due to gravity, ft/sec^2

N engine speed, rpm

V voltage applied to starter, volts

A starter current, amperes

REFERENCES

1. Anon.: Rolls-Royce Nene I. Flight, April 18, 1946, pp. 393-394.

2. Gold, Harold, and Straight, David M.: A Fuel-Distribution Control for Gas-Turbine Engines. NACA RM No. E8C08, 1948.

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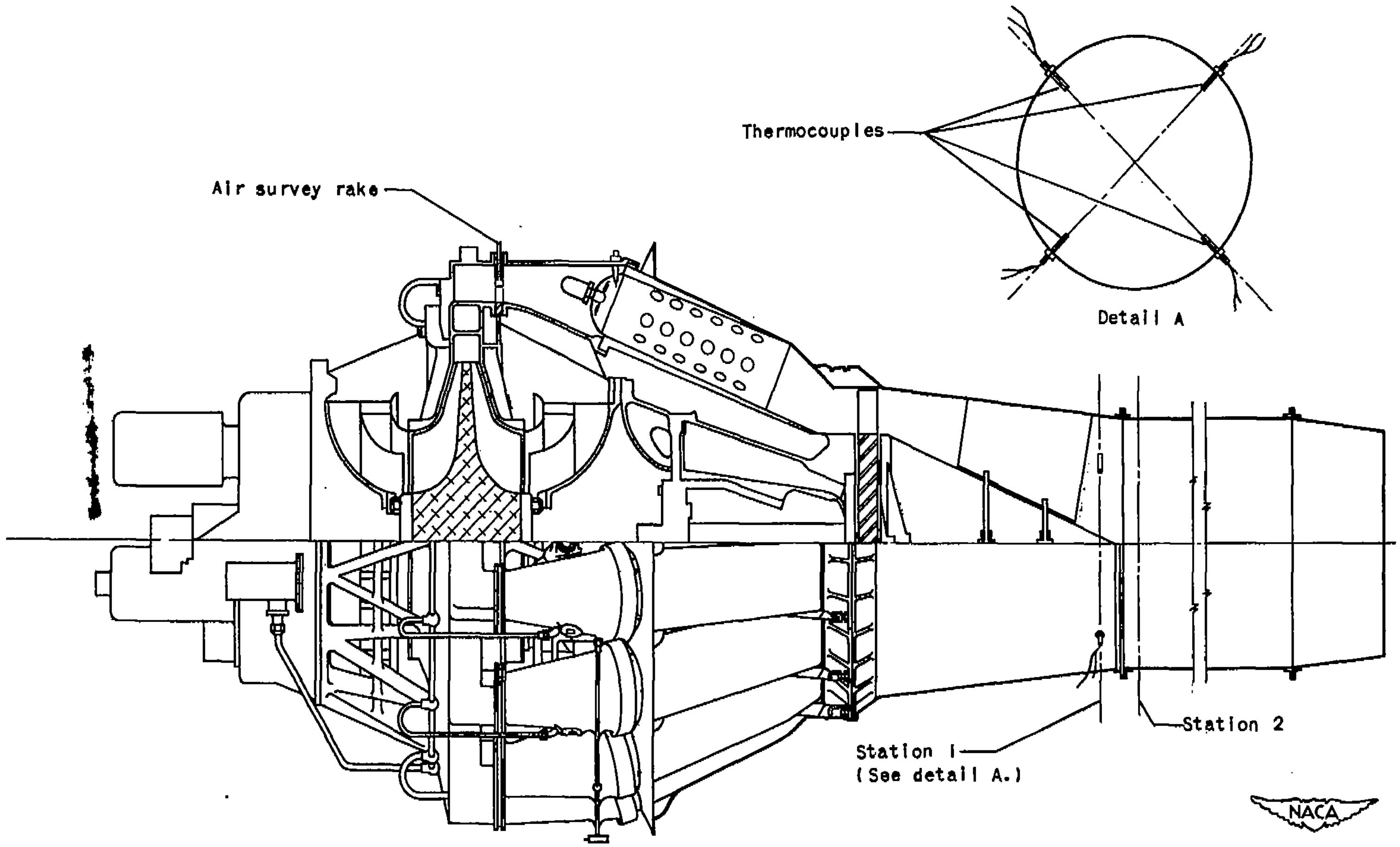

Figure 1. - Diagram of centrifugal-compressor, through-flow-type turbojet engine showing location of instrumentation.

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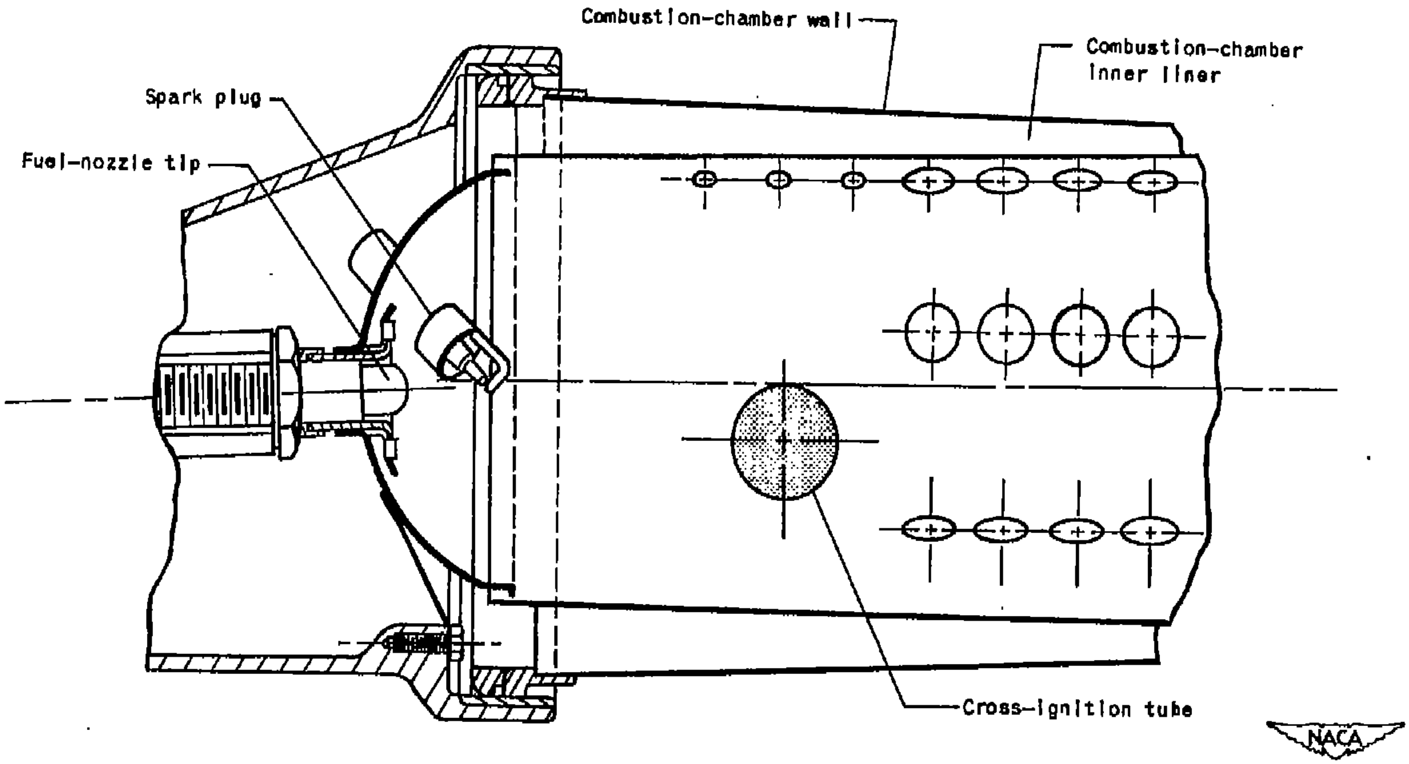
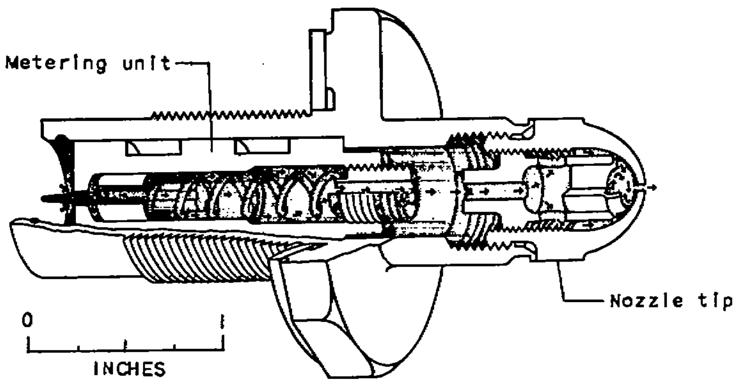
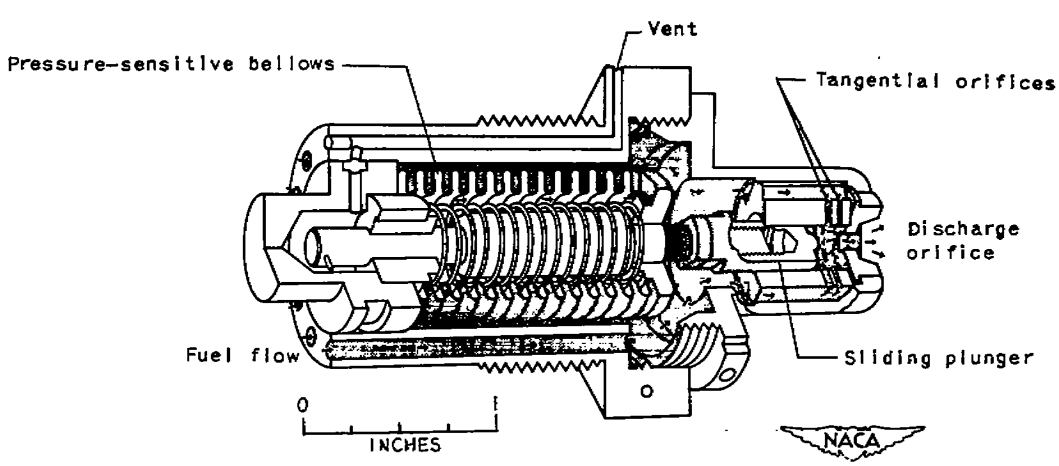


Figure 2. - Section of combustion-chamber assembly of centrifugal-compressor, through-flow-type turbojet engine.



(a) Fixed-orifice type.

Figure 3. - Fuel-nozzle assembly.



(b) Variable-orifice type.

Figure 3. - Concluded. Fuel-nozzle assembly.

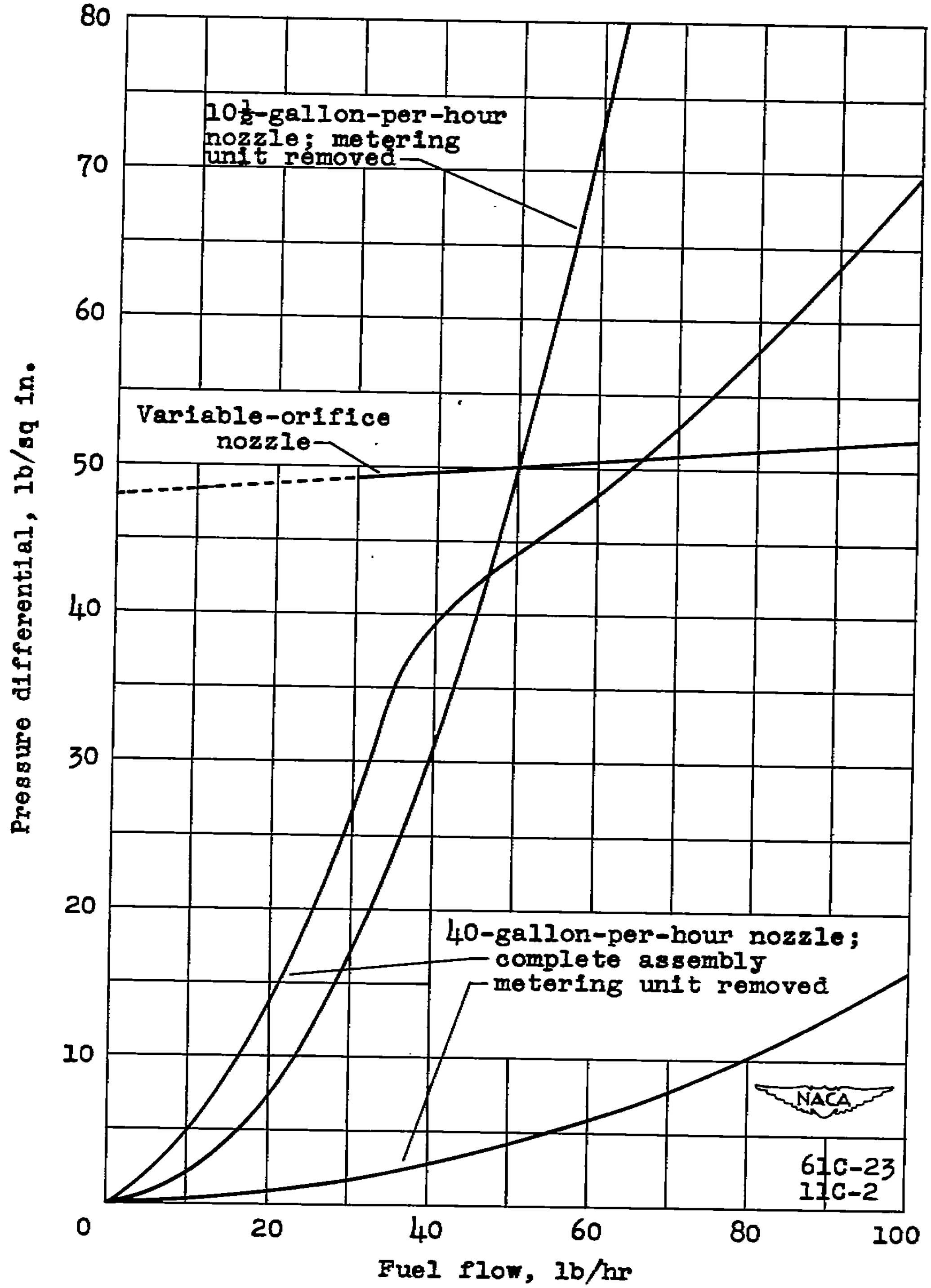


Figure 4. - Hydraulic characteristics of fuel nozzles. Fuel, AN-F-32.

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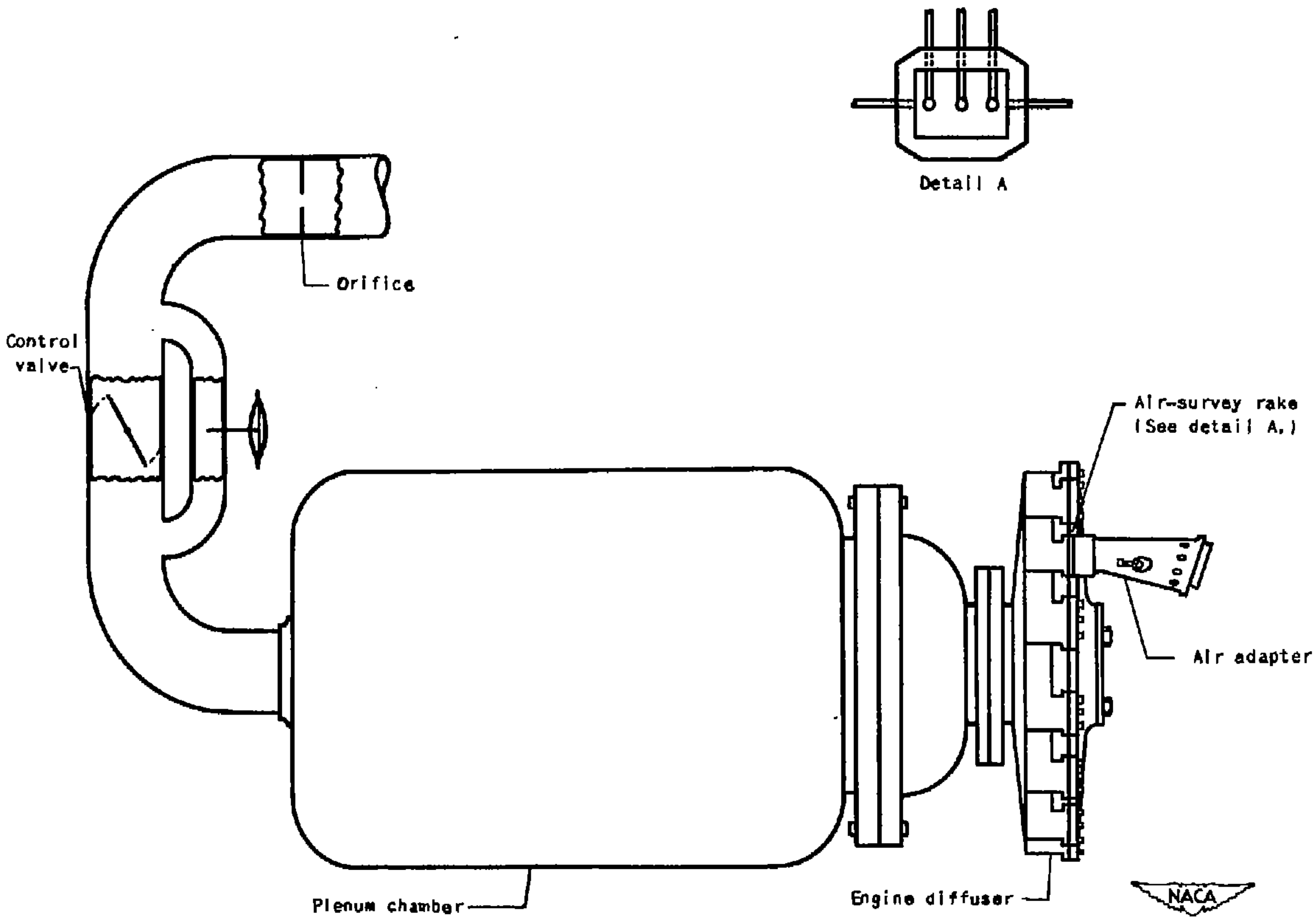

Figure 5. - Sketch of air-survey-rake calibration equipment.

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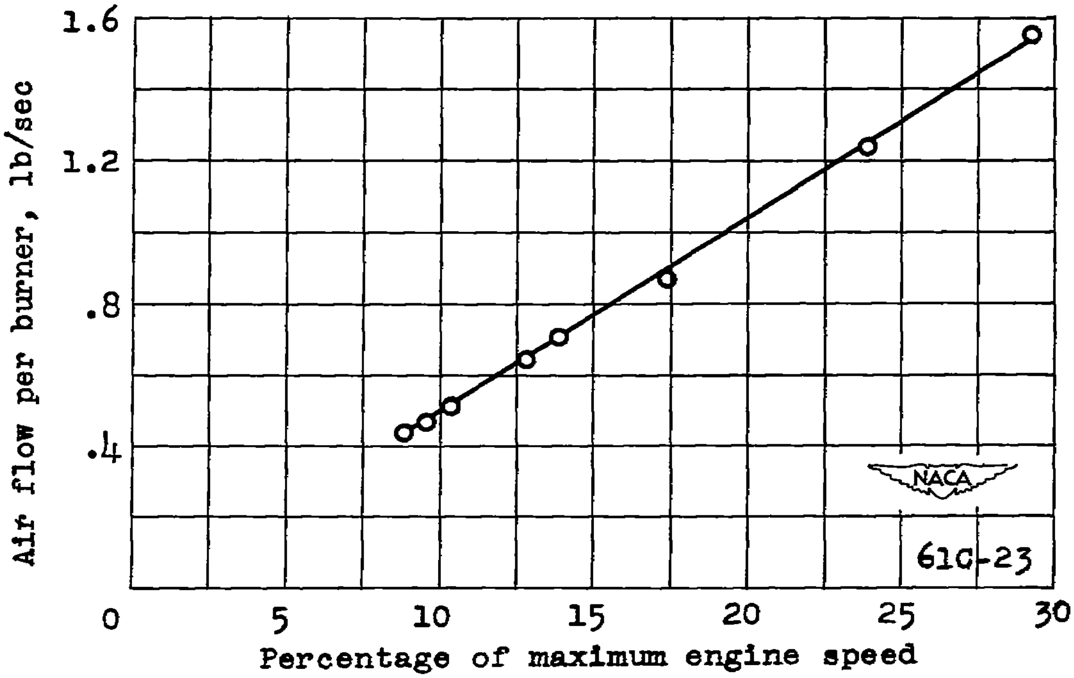

Figure 6. - Air flow to one combustion chamber. Starting speed range.

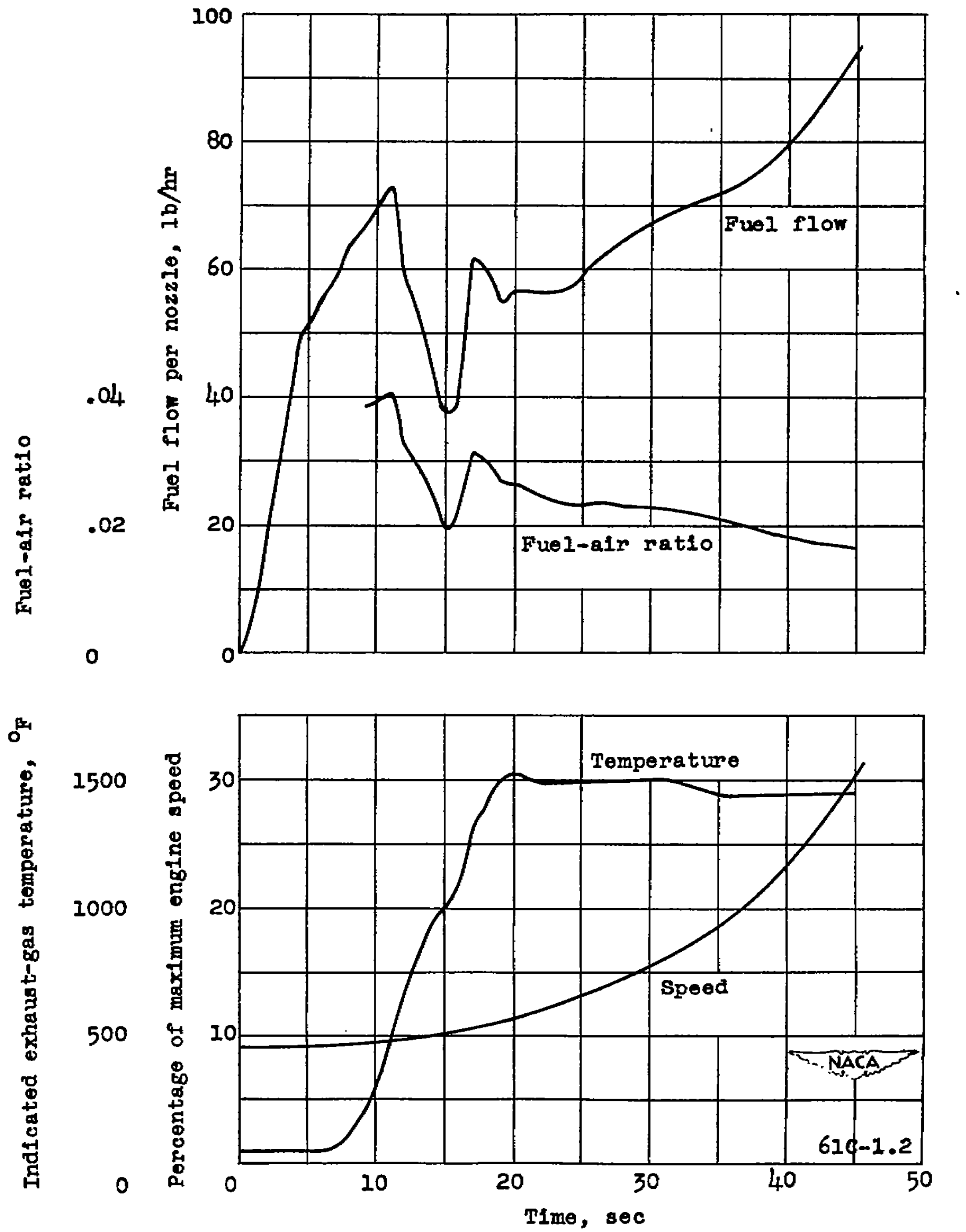

Figure 7. - Starting characteristics of centrifugal-compressor, through-flow-type turbojet engine with ignition at 9 percent of maximum engine speed. Large fuel nozzle rated at 40 gallons per hour at 100 pounds per square inch pressure differential.

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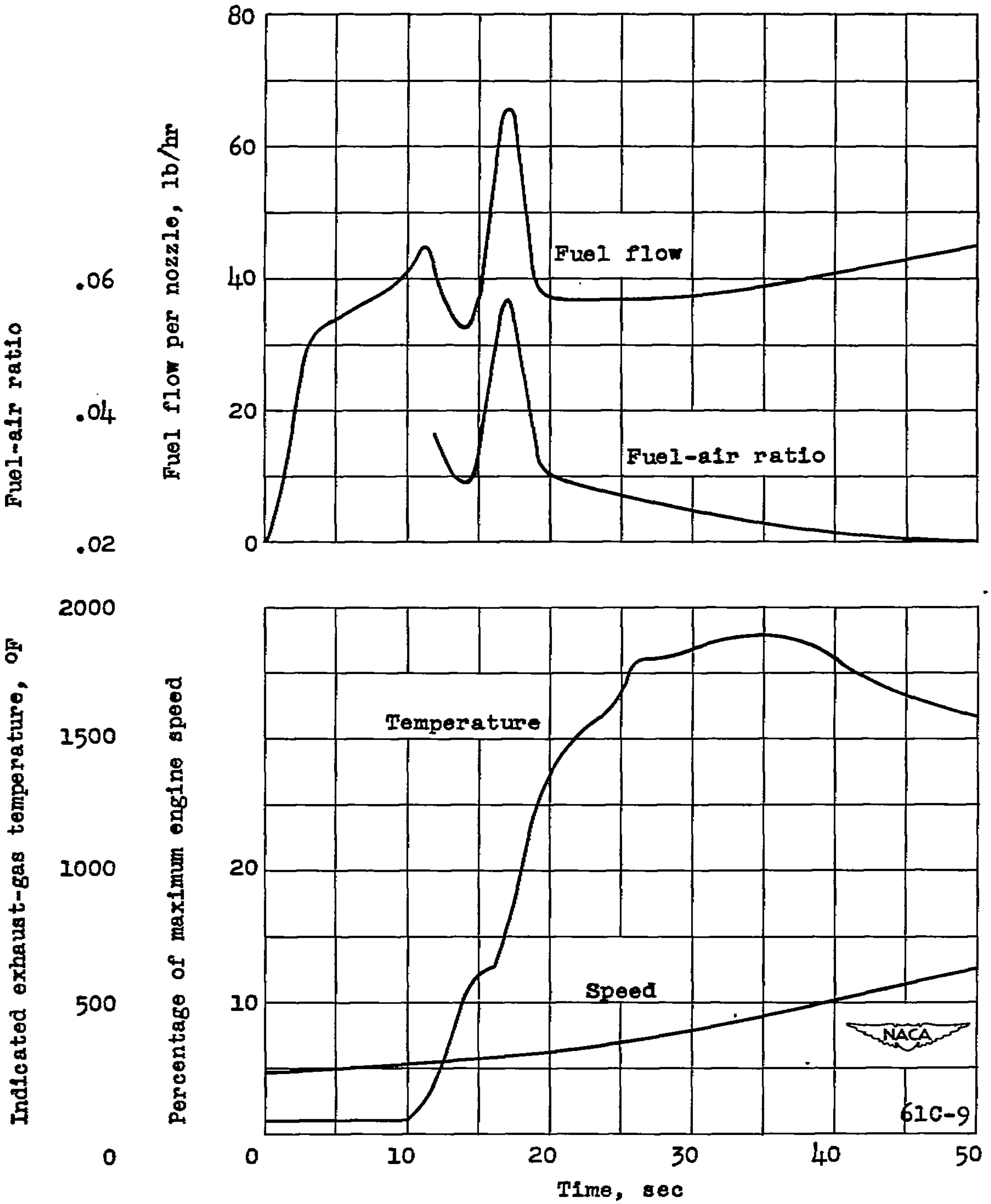

Figure 8. - Starting characteristics of centrifugal-compressor, through-flow-type turbojet engine with ignition at 5 percent of maximum engine speed. Large fuel nozzle rated at 40 gallons per hour at 100 pounds per square inch pressure differential.

(a) Fuel flow, 40 pounds per hour.

(b) Fuel flow, 60 pounds per hour.

Figure 9. – Degree of atomization and position of spray cone relative to spark plug. Large fuel nozzle rated at 40 gallons per hour at 100 pounds per square inch pressure differential; fuel, AN-F-32; no air flow.

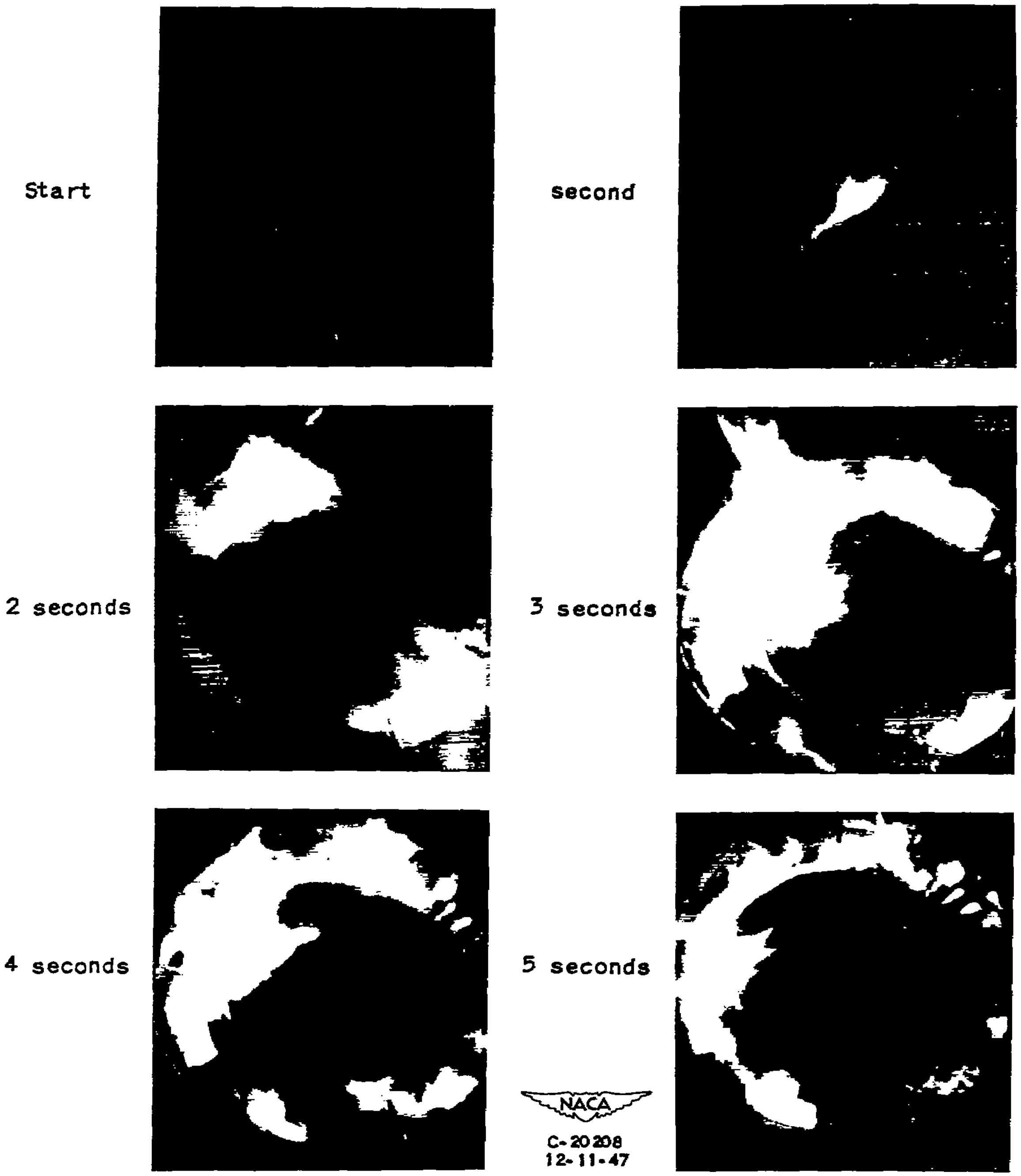

Figure 10. – Views taken looking toward turbine wheel from behind engine indicating ignition delay in combustion chambers not equipped with spark plugs. Large fuel nozzles rated at 40 gallons per hour at 100 pounds per square inch pressure differential; fuel, AN-F-32; spark-plug locations, 11 and 5 o'clock positions. Time is from first visibility of flame. Jet nozzle, exhaust pipe, and tail cone removed.

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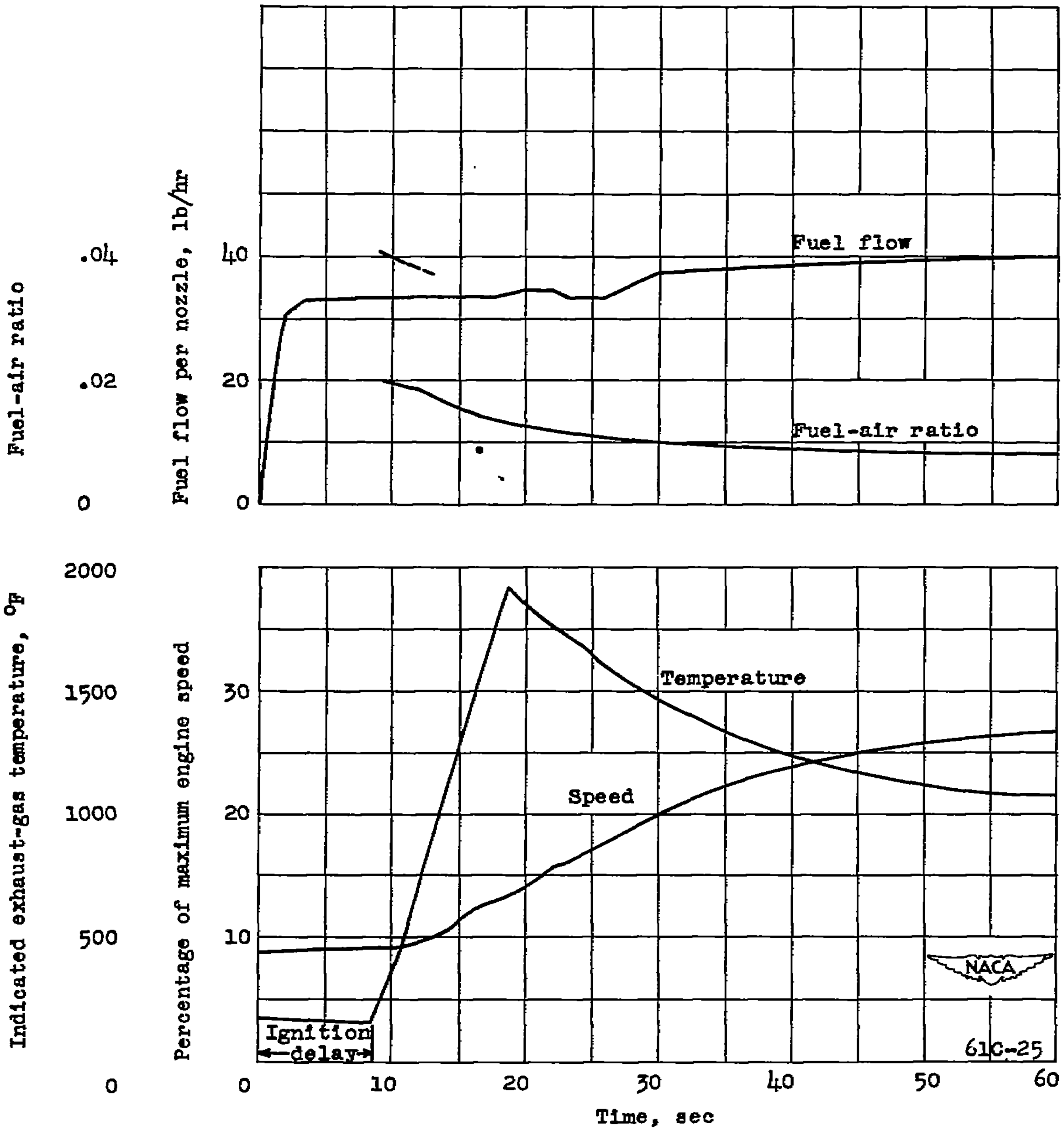

Figure 11. - Effect of delaying ignition by delaying ignition spark on maximum temperatures reached. Small fuel nozzles rated at 10.5 gallons per hour at 100 pounds per square inch pressure differential. Dashed curve indicates total fuel-air ratio, which would be attained assuming that all fuel supplied before ignition burns in 4 seconds following ignition.

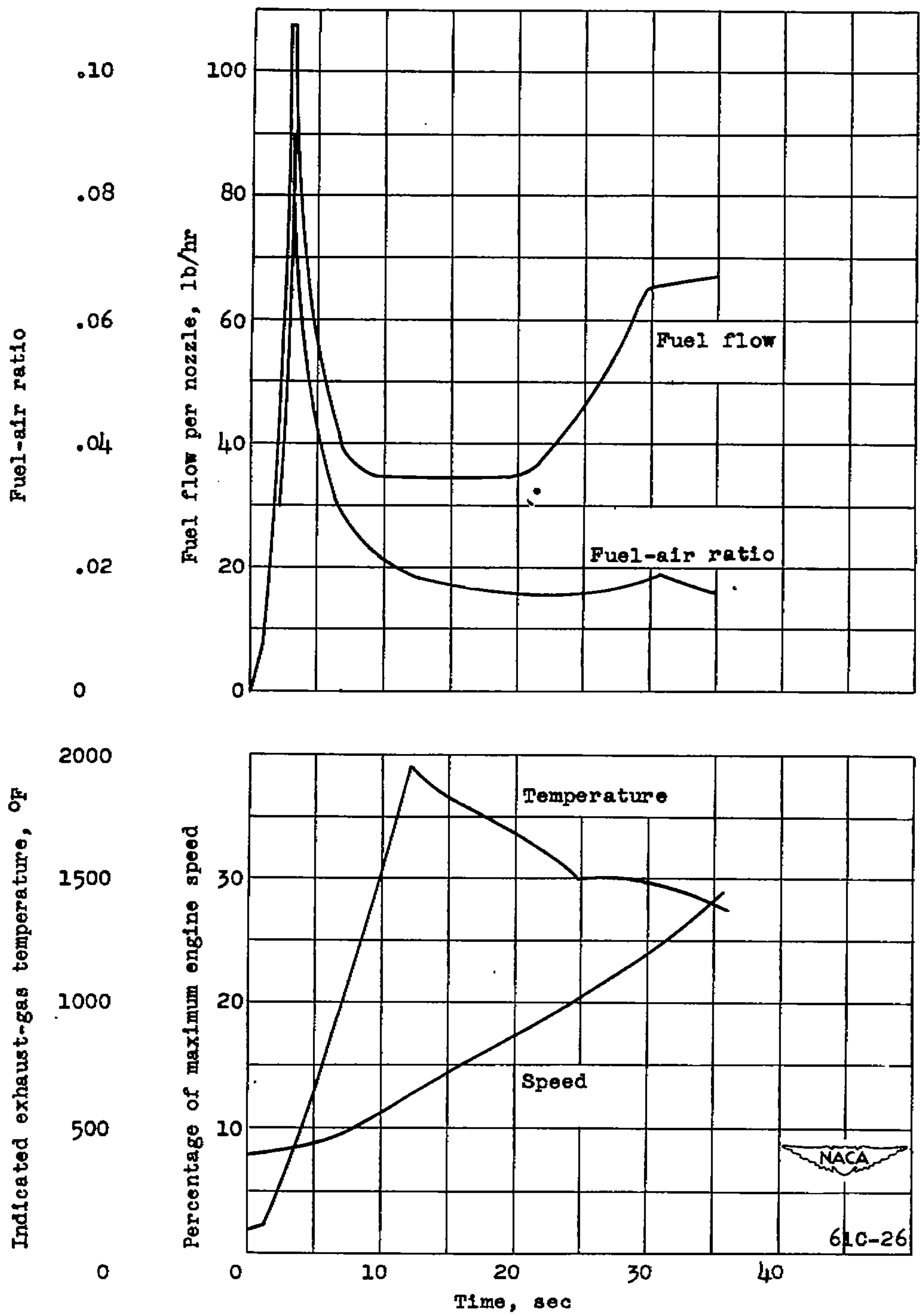

Figure 12. - Effect of high fuel-flow rate on starting characteristics. Small fuel nozzles rated at 10.5 gallons per hour at 100 pounds per square inch pressure differential.

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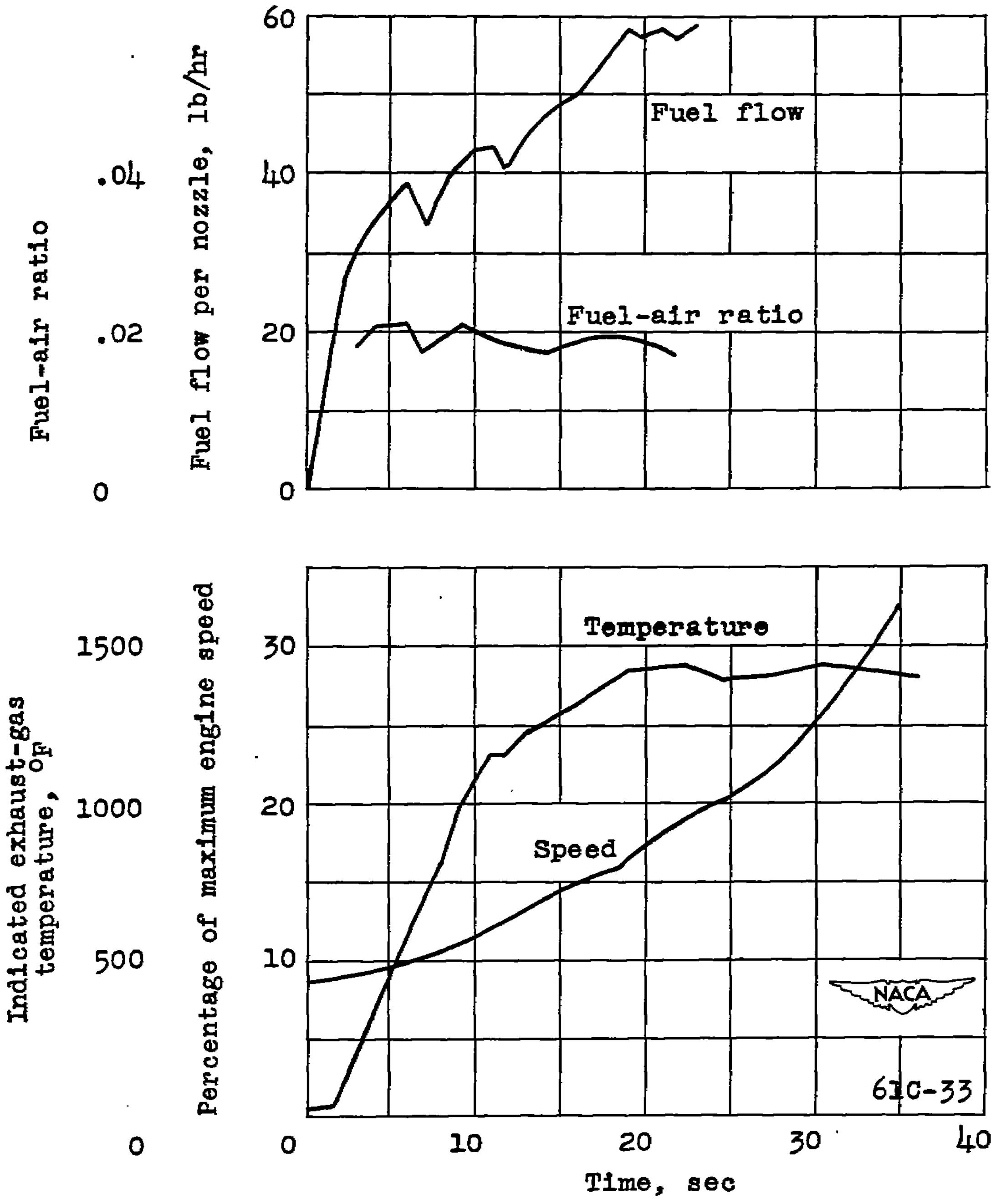
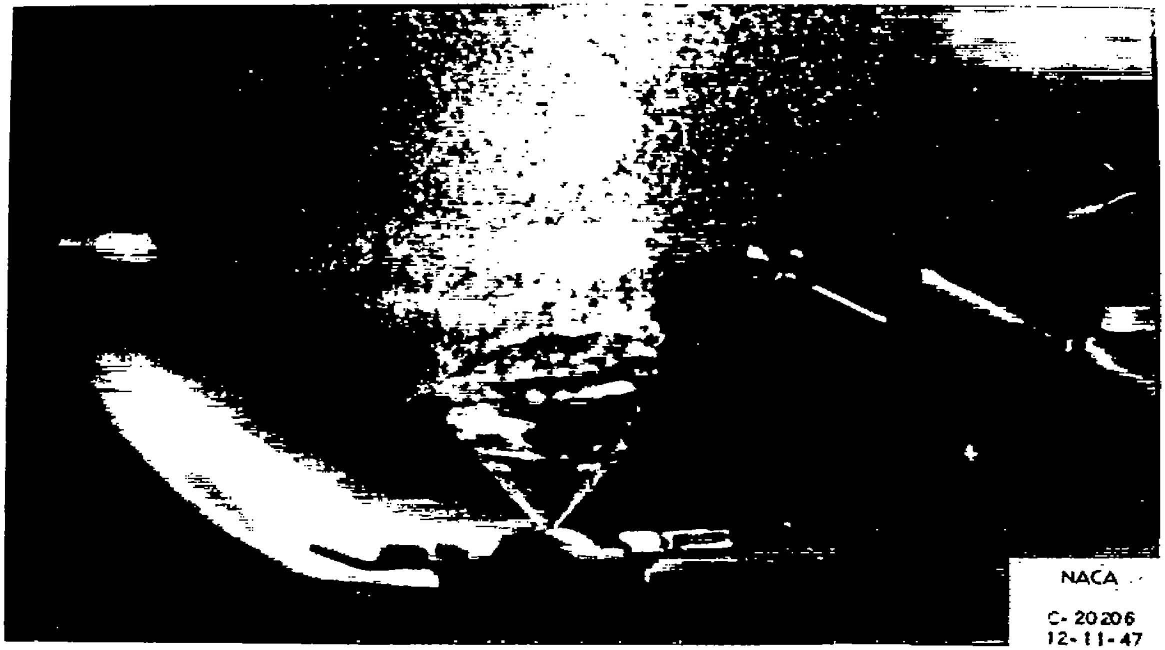


Figure 13. - Starting characteristics of centrifugal-compressor, through-flow-type turbojet engine. Small fuel nozzles rated at 10.5 gallons per hour at 100 pounds per square inch pressure differential.



(a) Fuel flow, 20 pounds per hour.

(b) Fuel flow, 30 pounds per hour.

Figure 14. – Degree of atomization and position of spray cone relative to spark plug. Small fuel nozzle rated at 10.5 gallons per hour at 100 pounds per square inch pressure differential; fuel AN-F-32; no air flow.

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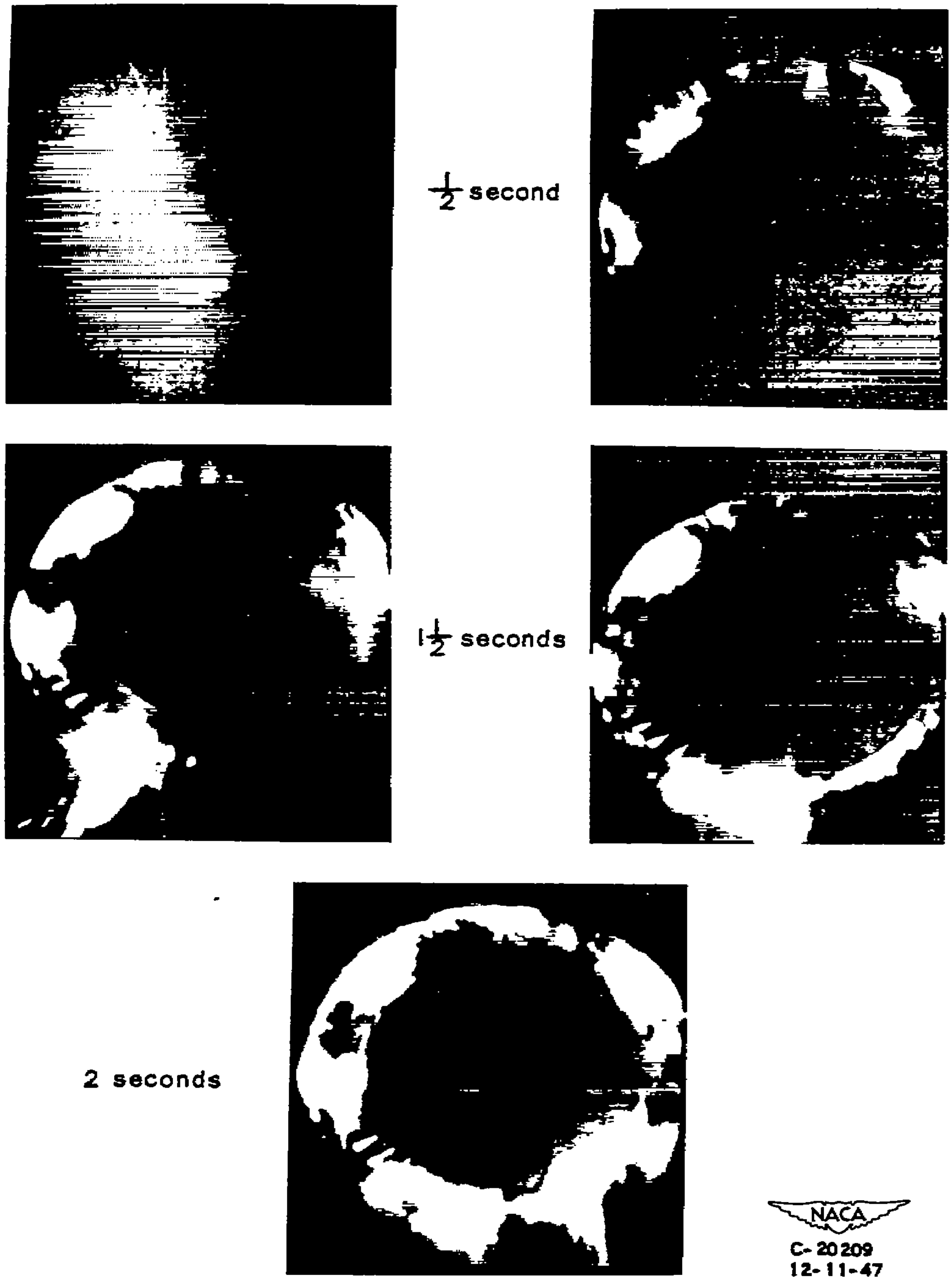

Figure 15. – Views taken looking toward turbine wheel from behind engine indicating ignition delay in combustion chambers not equipped with spark plugs. Small fuel nozzles rated at 10.5 gallons per hour at 100 pounds per square inch pressure differential; fuel, AN-F-32; spark-plug locations, 11 and 5 o'clock positions. Time is from first visibility of flame. Jet nozzle, exhaust pipe, and tail cone removed.

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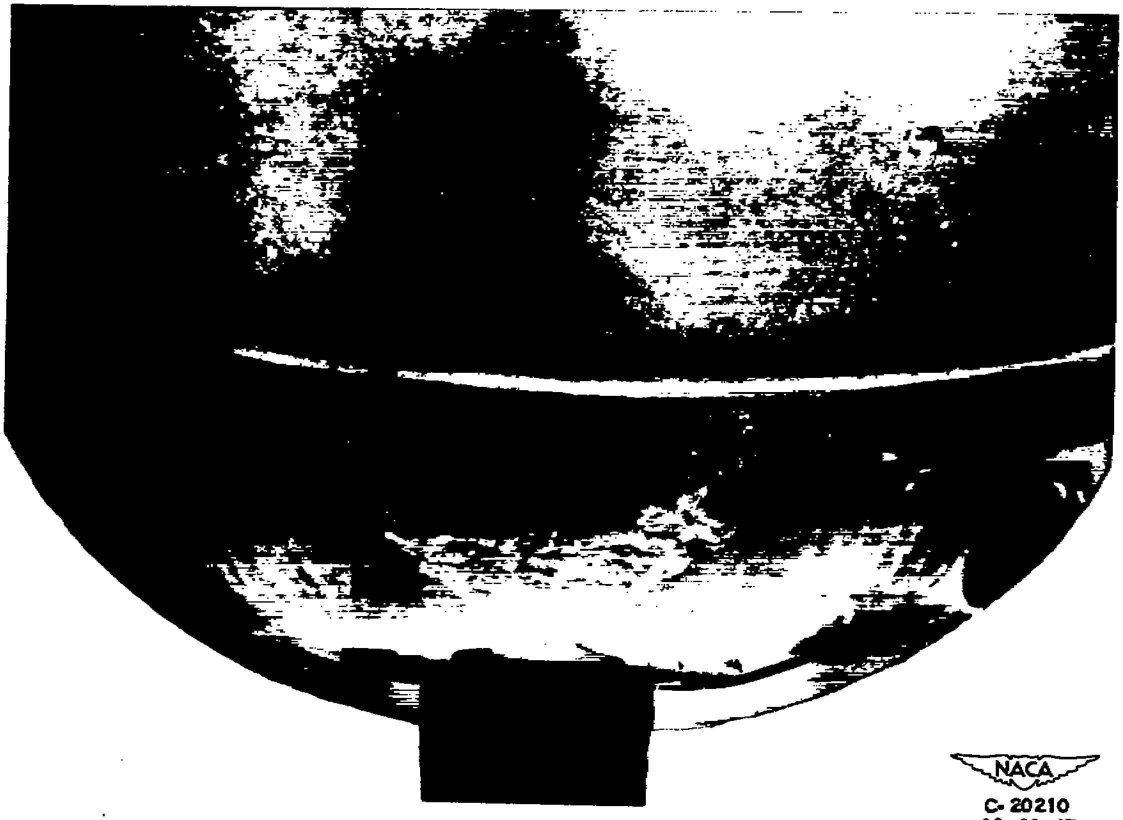

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Figure 16. – Degree of atomization and position of spray cone relative to spark plug. Variable-orifice fuel nozzle; fuel flow, 30 pounds per hour; fuel, AN-F-32; no air flow.

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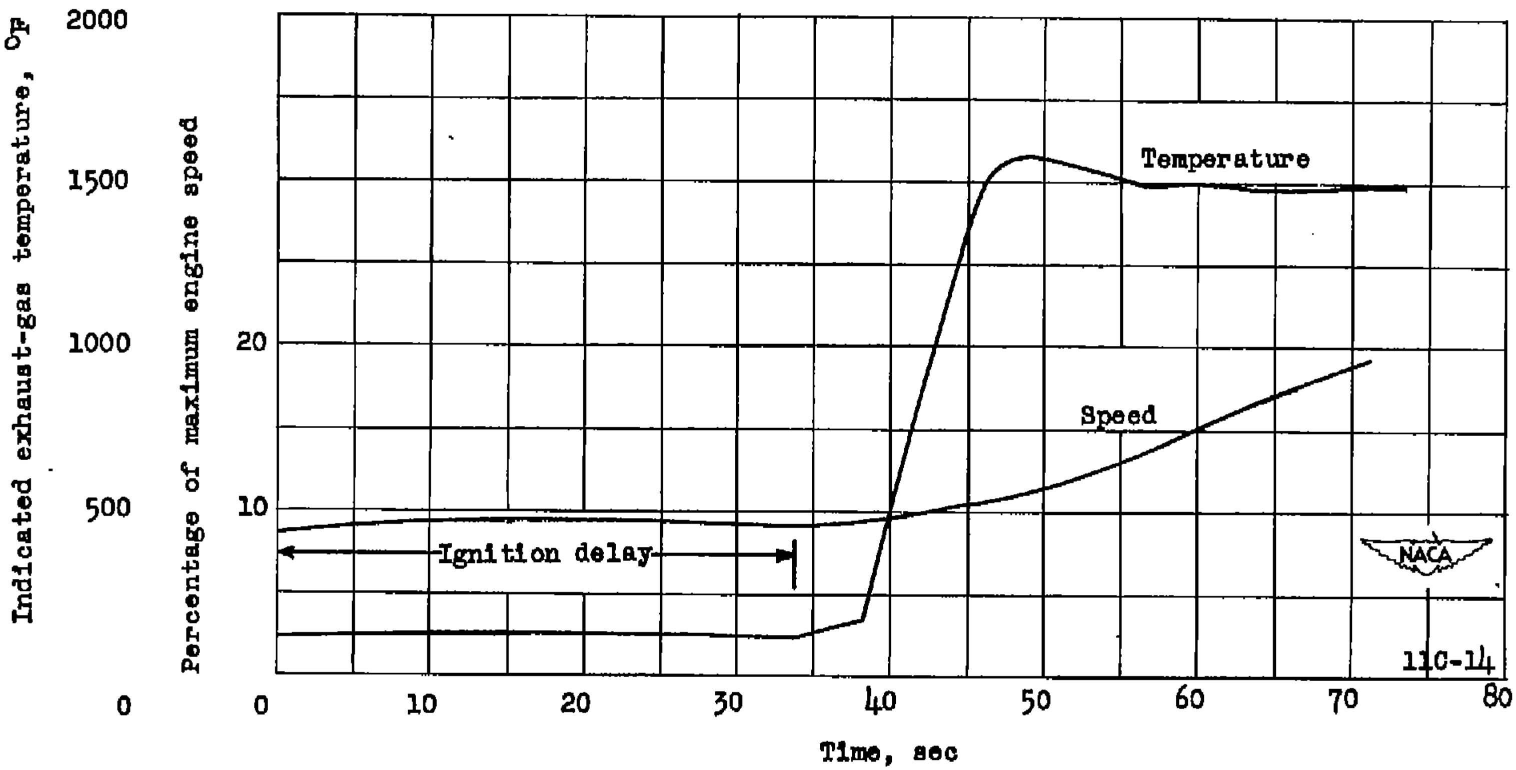

Figure 17. - Effect of delaying ignition by delaying ignition spark on maximum temperatures reached. Variable-orifice fuel nozzles.

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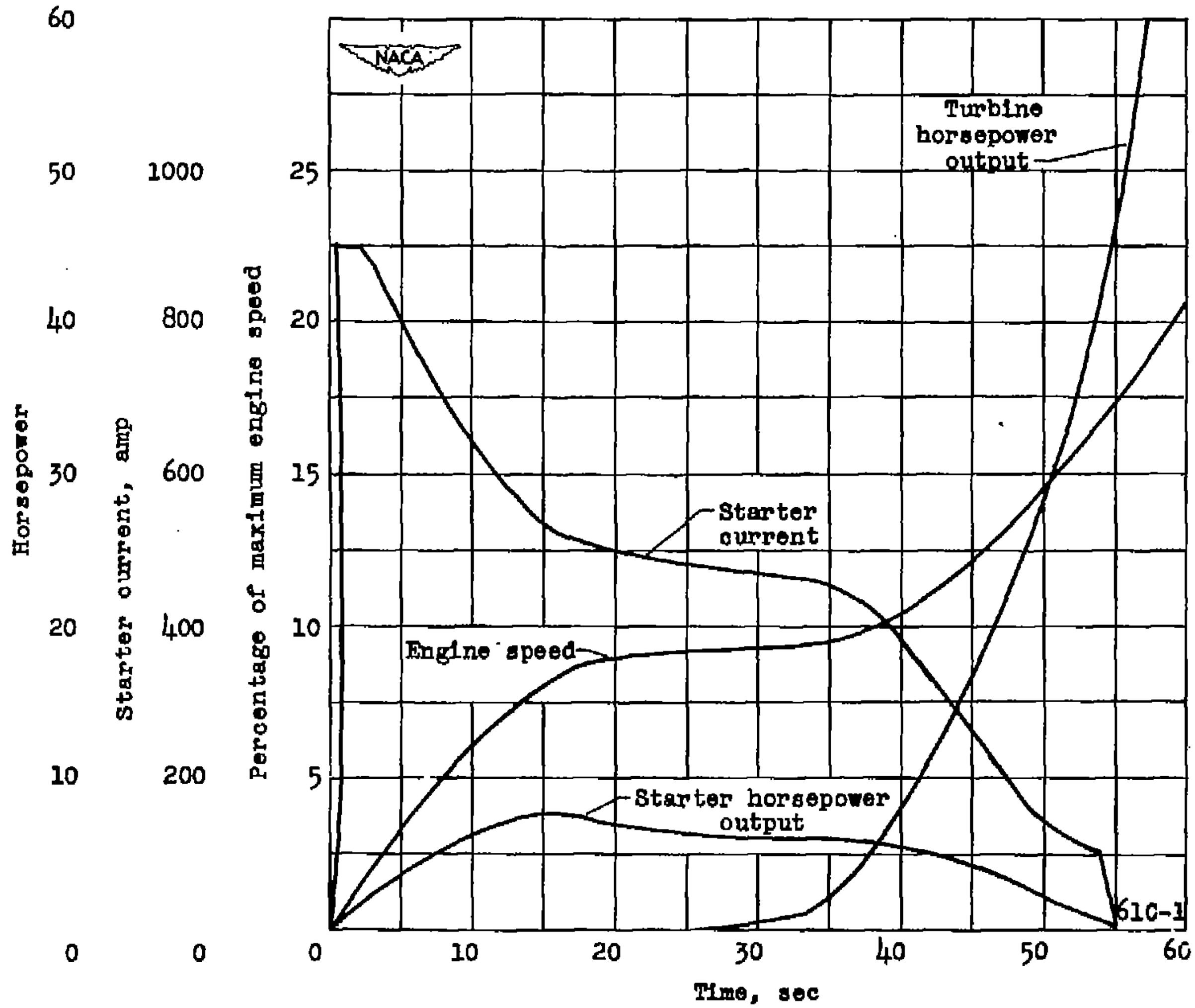

Figure 18. - Normal starting characteristics of centrifugal-compressor, through-flow-type turbojet engine. Ignition at 9 percent of maximum engine speed; large fuel nozzles rated at 40 gallons per hour at 100 pounds per square inch pressure differential; starter energy, 110 watt-hours.

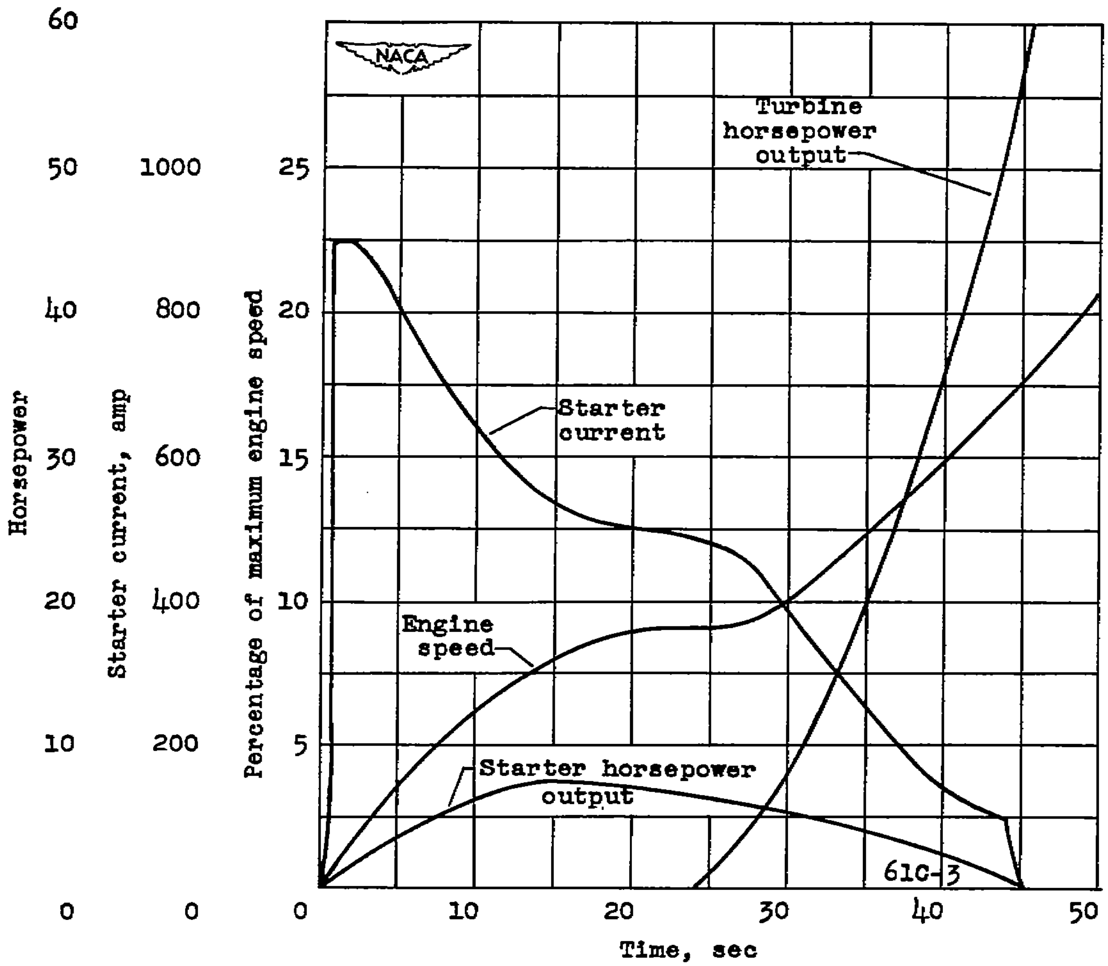

Figure 19. - Starting characteristics of centrifugal-compressor, through-flow-type turbojet engine. Ignition at 9 percent of maximum engine speed; small fuel nozzles rated at 10.5 gallons per hour at 100 pounds per square inch pressure differential; starter energy, 85 watt-hours.

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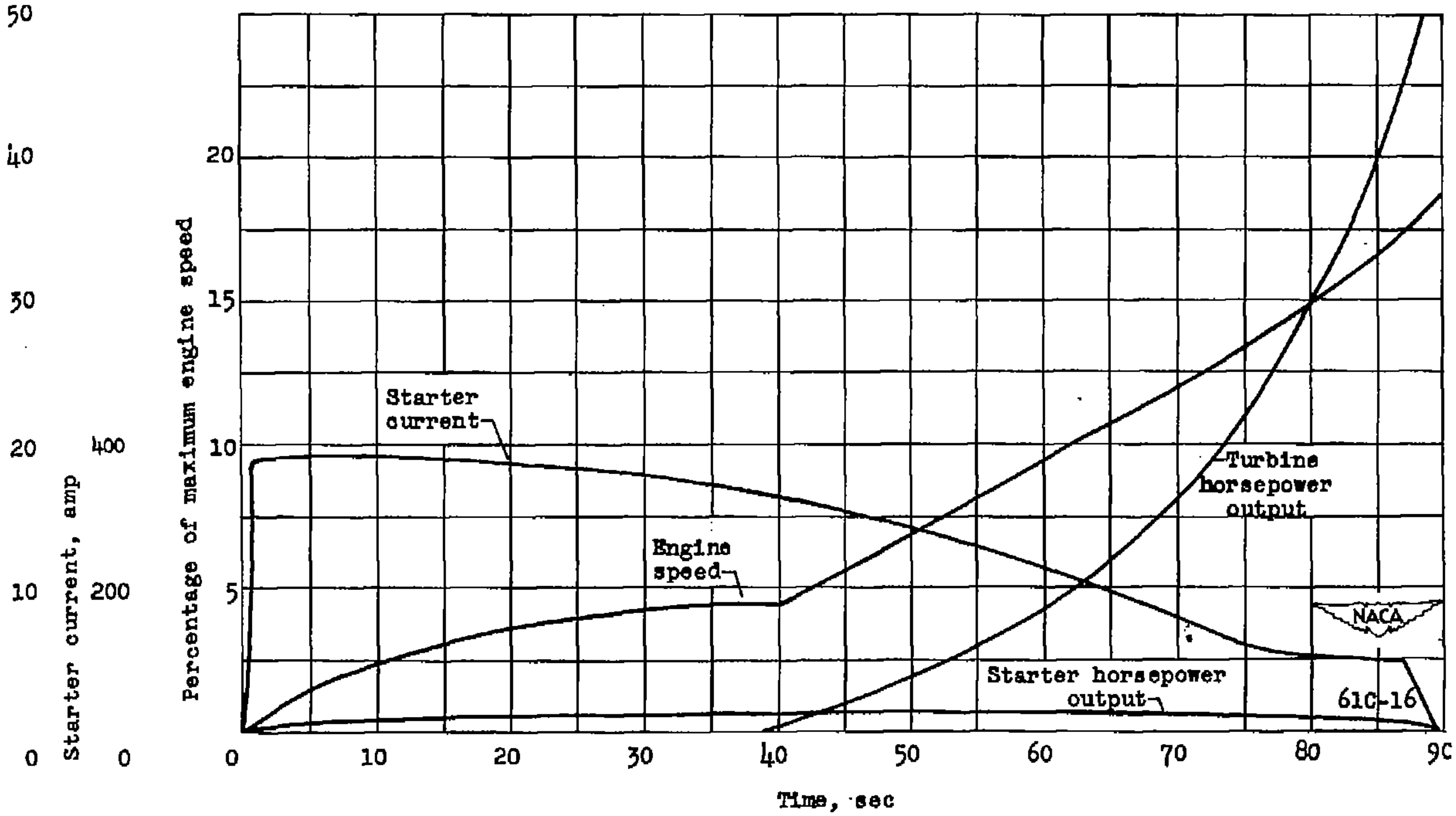

Figure 20. - Effect of reduced starter power and firing speed on starting characteristics of centrifugal-compressor, through-flow-type turbojet engine. Ignition at $4\frac{1}{2}$ percent of maximum engine speed; small fuel nozzles rated at 10.5 gallons per hour at 100 pounds per square inch pressure differential; starter energy, 62 watt-hours.

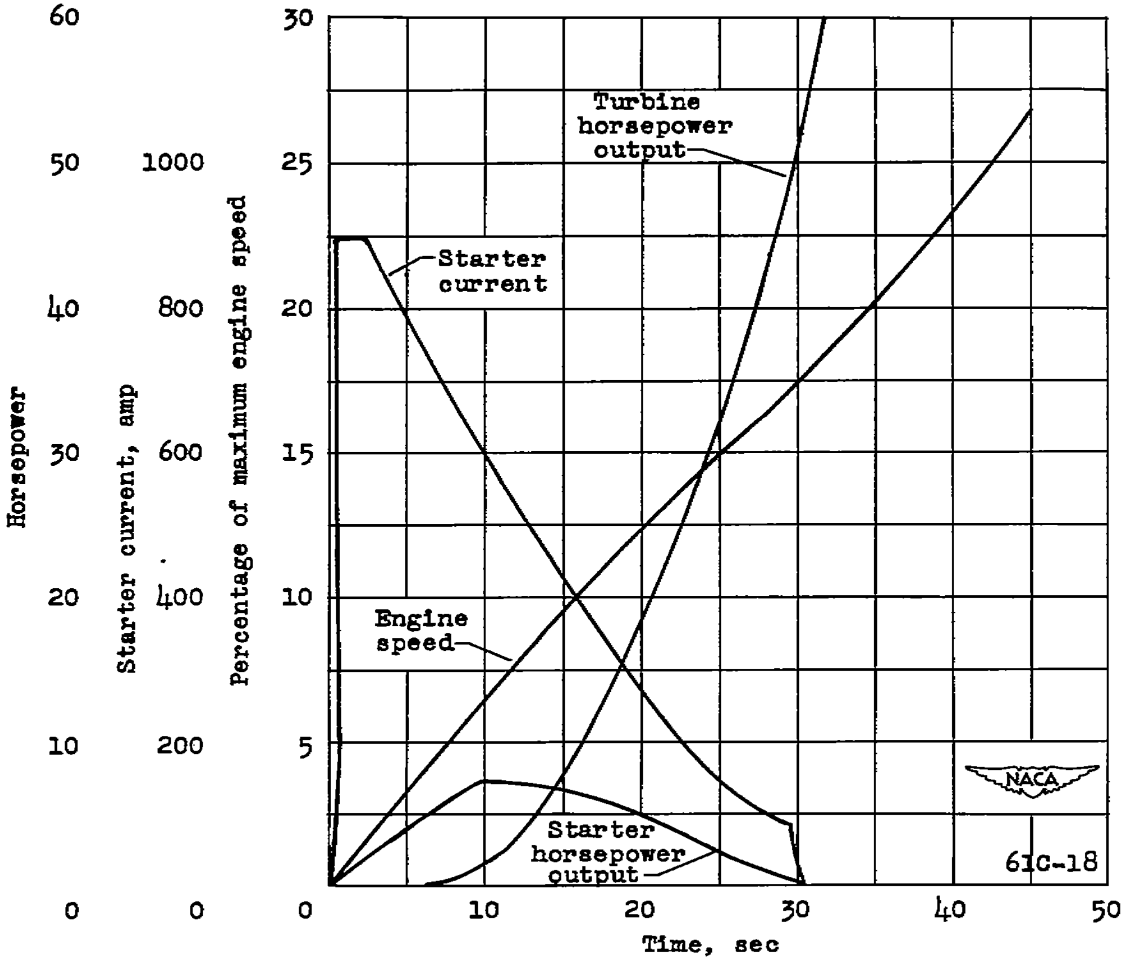

Figure 21. - Effect of reduced firing speed on starting characteristics of centrifugal-compressor, through-flow-type turbojet engine. Ignition at 4 percent of maximum engine speed; small fuel nozzles rated at 10.5 gallons per hour at 100 pounds per square inch pressure differential; starter energy, 50 watt-hours.